

Autonomous Image-Based Pointing for Planetary Flyby

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ABSTRACT

There is increasing emphasis on onboard autonomy in the design of future spacecraft. Image-based, closed-loop tracking and pointing, developed as part of the Autonomous Feature And Star Tracking (AFAST) project at the Jet Propulsion Laboratory (JPL), has emerged as one of the technology areas essential to realizing autonomous spacecraft. In this paper, we present an overview of our ongoing efforts to develop intelligent, onboard processing technology that will make it possible to realize such spacecraft. A mission scenario, a planetary small-body flyby, is used to illustrate the autonomous tracking/pointing technology addressed in the research.

Keywords: autonomy, image processing, shape characterization, feature detection, tracking

1 Introduction

NASA's future space missions (both planned and as-yet unknown) to explore Jupiter, Mars, comets, and asteroids will emphasize smaller, low-cost spacecraft with onboard autonomy. Successful implementation of onboard autonomy in spacecraft missions will not only minimize the mission-operation costs, but will also maximize the science return. Furthermore, such autonomy will be imperative for future small-body missions where the uncertainty in target knowledge and the communication time delay might render the traditional ground-based approach impractical or ineffective.

One of the key research areas in autonomous spacecraft technology is the development of an autonomous tracking and pointing system in which the target relative information is collected and processed on board and is based on image data. To realize such an autonomous onboard system for space applications, the relevant information on the target body must be extracted from the visual cues reliably and efficiently. Such information can then be provided to the guidance, navigation, and control (GNC) subsystem to autonomously navigate and control the spacecraft.

Despite the richness of the fields of image processing and computer vision, robust onboard processing of image data for space missions was never successfully demonstrated because of spacecraft processing capability

and memory limitations. However, recent advances in computer vision algorithms and microtechnology have provided us with a unique opportunity to apply the vision technology to automating the process of obtaining science images during space exploration missions.

JPL's Autonomous Feature And Star Tracking (A FAST) project has been actively engaged in developing an intelligent sensing and processing technology that is based on space image data and will enable the realization of an intelligent, autonomous, image-based tracking and pointing system.⁴ A great deal of our effort has **been** focused on developing and testing low-level vision algorithms for our applications by using the vast volume of raw data from Voyager's image library. Our major emphasis has been focused on *automated processing, robustness, and computational efficiency*.^{1,4} A planetary flyby example has been constructed to illustrate the concept and feasibility of our proposed closed-loop image-based tracking and pointing system. A complete flyby mission scenario spanning the distant-, near-, and close-encounter phases for a spherical body was presented previously;¹ the key technical elements included acquisition/tracking of single or multiple bodies, limb detection, quadratic curve estimation, and autonomous mosaicking.

As a result of the increasing interest in the exploration of small celestial bodies that has been shown by the space community, asteroid and comet missions are currently being actively planned under several NASA programs such as Discovery and New Millennium. However, the ground-based *a priori* positional knowledge of small bodies tends to be uncertain as a result of the small target size and distance from the Earth. Furthermore, unlike a large planetary body, small bodies are typically irregular in shape. A priori characterization of their 3-D geometry will be impractical, if not impossible, using ground-based technology. If we compound these facts by current economic constraints, the autonomous spacecraft approach becomes the only feasible solution for carrying out small-body missions, and our proposed closed-loop, image-based pointing and tracking technology will be essential to ensure mission success with maximal science return.

Our focus for the past year has been on technology development pertaining to small-body applications, asteroids in particular. As is evident from Galileo's encounters with Gaspra and Ida, asteroids can best be described as irregularly shaped spinning bodies. Therefore, a 3-D characterization of the target body during the approach is crucial to the success of the mission. However, due to the geometry of the Sun, spacecraft, and target, body terminators are typically visible from the spacecraft view. As a result, characterizing the shape of the target will require developing robust, modeling techniques for shape recovery from shading in general.

For missions involving flyby of slow-spinning asteroids such as Gaspra, the encounter time is much shorter than the spin period of the target body. In this situation, a complete 3-D shape characterization of the target body is not necessary, since the observable area of the target does not vary very much during encounter. It is found that simple rectangular bounding is sufficient to characterize the size of the target when the target's angular diameter as observed from the spacecraft is less than the camera's field-of-view (FOV). As is demonstrated in this study, the information on the size and aspect ratio that is provided by the rectangular bounding enables us to plan and carry out autonomous operations such as mosaicking. When the entire target cannot be observed within the FOV, rectangular bounding is no longer applicable. In this case, robust feature detection and mapping are employed to update the relevant information for mosaicking and tracking operations continuously.

In this paper, we provide a status update for our research efforts that goes beyond our previous report.¹ An AFAST-driven planetary flyby scenario is presented in Section 2, where the subjects of shape characterization, and feature detection, mapping, and tracking are also discussed. To facilitate the integrated testing of our algorithms, an AFAST 3-D visualization testbed based on an SGI platform was developed and is described in Section 3. By incorporating high-resolution spacecraft and celestial body models, along with accurate ephemeris data generated by the JPL NAIF toolkit, this visualization testbed can generate the realistic scenes needed by the AFAST tracking and pointing system in real time. This unique capability enables us to verify as well as to demonstrate our proposed image-based tracking and pointing technology for small-body applications in a real-time simulation environment. Finally, some future work is described.

2 AN AFAST-DRIVEN PLANETARY FLYBY

our proposed AFAST-based target acquisition, tracking, and pointing sequence for a planetary flyby mission scenario can be considered in terms of various encounter phases. It consists of the following elements:

1. Distant Encounter:

Prior to acquiring target bodies, the autonomous star identification function will provide attitude information continuously. Using this information and the propagated inertial vector associated with the target body, the spacecraft will turn and attempt to point the imaging camera to the desired target. However, due to the uncertainty in the knowledge of the target position, a search area of appropriate size around the derived pointing direction will be necessary to ensure successful acquisition of the target. At this distance, the target can be isolated by clustering techniques, and a simple centroid can be used as a pointing reference and as a target-relative position measurement for spacecraft attitude control and navigation. For a scenario where multiple bodies might appear in the same camera field-of-view, clustering of distinct targets and center-of-mass tracking can be carried out.¹

2. Near Encounter:

During this period, the object size is estimated continuously. For spherical bodies, differentiation of limb from terminator can be done without *a priori* Sun position knowledge,⁵ and a closed-form solution for the size (the radius in pixels) can be obtained in the least squares sense.¹ For irregularly shaped bodies such as asteroids, a 3-1 shape characterization is generally required. However, for slow-spinning asteroids, rectangular bounding provides excellent information about the target size. Continuous estimation of the target size can then be used to plan and refine the autonomous mosaicking operation.⁶ In the meantime, the feature-detection function will be initiated. A feature map on the target surface model will be established based on the feature points detected. The frame-to-frame correspondence of registered feature points can be used for tracking as well as size estimation.

As the spacecraft approaches the target body, at some point, the entire target body will not be captured within the same image frame and rectangular bounding will no longer be applicable for size estimation. In this case, feature-based tracking will be the most critical spacecraft function for providing the information on the target body.

3. Close Encounter:

Feature detection, mapping, and tracking will be the primary functions during this encounter phase. AFAST technology will not only enable tracking of prominent features for high-resolution science images, but will also provide frame-to-frame correspondence of registered feature points for continuous updating the target size and for determining the starting time of the autonomous mosaicking operation. Furthermore, the overall mosaic size can be determined autonomously on the basis of the aspect ratio of the estimated bounding rectangle.

Figure 1 shows a time line corresponding to the encounter sequence stated above where T_{FT} and T_{AM} are the starting times for feature tracking and autonomous mosaicking, respectively. Some of the technical elements have been discussed previously.⁷ In the rest of this section, we will provide an overview of shape characterization; feature detection, mapping, and tracking; and mosaic sequence planning.

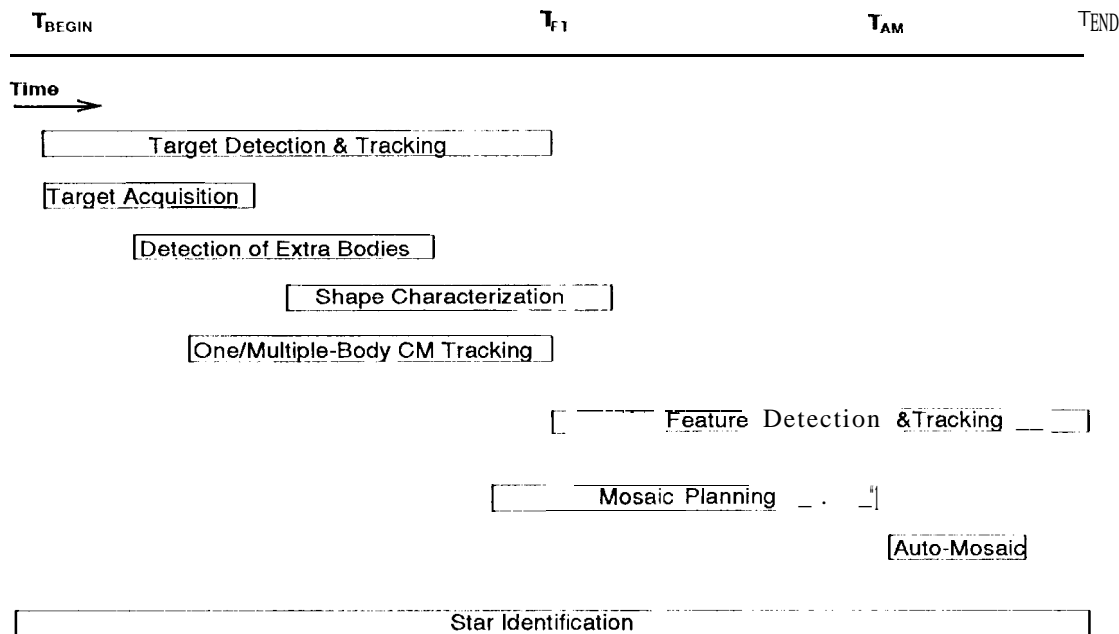


Figure 1 Target acquisition and tracking sequence for planetary flyby

2.1 SHAPE CHARACTERIZATION OF IRREGULARLY SHAPED BODIES

The large celestial bodies are typically characterized as spherical objects. Their shape characterization and size estimation are quite straightforward and are based on the detected limb.¹ For small bodies such as asteroids, shapes can be characterized as irregular at best, as is evident from the results of ground-based radar observations of near-Earth asteroids such as Castalia² and from the Jupiter-bound Galileo spacecraft's encounter with Gaspra and Ida. In general, establishing a complete 3-D model of an irregularly shaped body on the basis of images is quite difficult. However, such shape characterization will be required eventually for any close-up operation in a flyby or an orbiting mission.

During close encounter in a flyby mission, a mosaicking sequence is designed to acquire high-resolution images. To achieve the maximal science return, such a sequence should be generated on board and based on estimates of the shape and size of the target body. For slow-spinning asteroids (Gaspra, for example), complete shape characterization may not be necessary for the purpose of mosaicking. In such cases, a simple rectangular bounding of the asteroid has been found to be quite effective in generating a mosaic pointing sequence autonomously. The bounding rectangle allows the spacecraft to monitor and predict the size of the asteroid, which can be used in determining the appropriate time to start the mosaicking operation. Furthermore, the aspect ratio of the rectangle can be used to determine the mosaic size.

During the near-encounter phase of an asteroid flyby, the boundary points of the asteroid can be extracted by using standard segmentation or edge-detection techniques.¹ Given a set of the boundary points, the corresponding scatter matrix can be generated. The bounding rectangle can then be generated using the two eigenvectors of the scatter matrix and the centroid of the boundary points.

Figure 2 shows an example of bounding an irregularly shaped object with a rectangle.

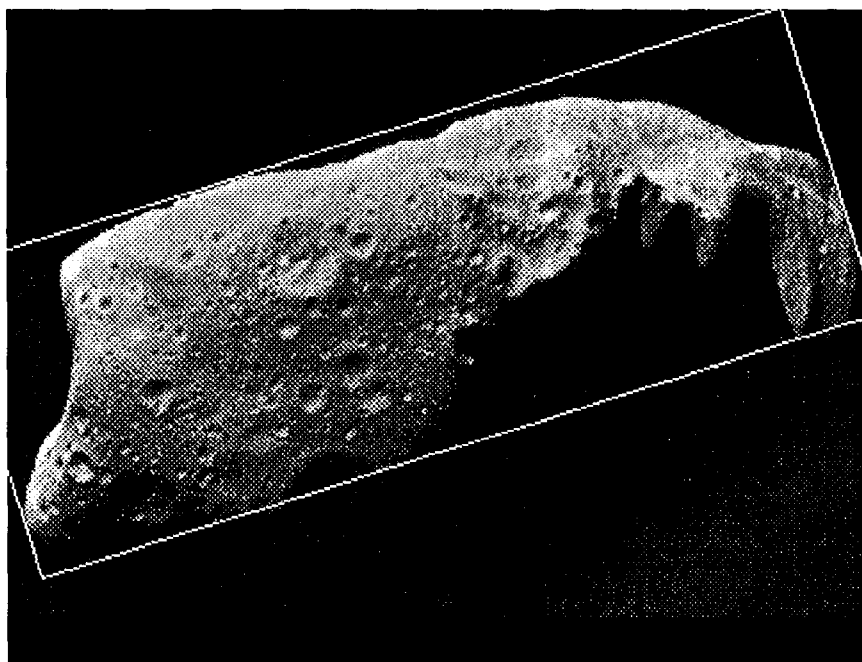


Figure 2 Rectangular bounding of asteroid Ida

2.2 FEATURE DIRECTION AND TRACKING

The goal of the feature-detection function of our proposed system is to extract suitable features from the sensor images while the spacecraft is approaching the target body. The algorithm selected must operate within the time and space constraints imposed by existing space-certified hardware and not require operator interaction (i.e., it must be fully autonomous). Since the detected features are to be used as markers for pointing purposes, the algorithm needs to detect them over the wide range of lighting, perspective, and scale changes which are typical of a planetary flyby.

Instead of having the algorithm identify feature regions, our strategy is to have it identify actual points in the image that are relatively stable with respect to perspective and scale changes. To accomplish this, the image is convolved with Gabor filters at different resolutions and orientations.³ The points corresponding to the local maxima of the resultant differenced image are considered to be *candidate* feature points from the original sensor image. Additional criteria are employed to ensure that the majority of the feature points used to compose the feature map do correspond to suitable planetary surface properties and are not simply image noise or lighting artifacts. Once constructed, the feature map provides support for pointing estimation when alternative methods

(e.g., limb determination) are no longer effective. A feature map can then be generated from the detected feature point.

The feature map generated during a flyby is useful in two ways. It supports preplanned pointing operations by providing feedback about the sensor attitude, which is determined by the correspondence between the current image and the prediction. It also allows pointing operations to be more content driven. Registered points serve to determine the frame-to-frame correspondence during tracking so that the sensor FOV can be centered on a specific feature.

The point-mapping operation involves locating the feature points found by the detection algorithm onto an assumed model of the target object. In our current implementation, the feature map is generated from a single image. The plan for mosaicking is constructed (i.e., a sequence of pointing operations is referenced to the object's center of mass) using the information from the change in apparent object size over the course of the encounter. This plan is then converted to actual surface areas on the model on the basis of the spacecraft's estimated trajectory and the apparent object size (which establishes resolution). Viewable regions are then extracted from the image, and the detection algorithm locates the feature points in these areas. The correspondence between the stored feature points and the predicted ones (generated according to the mosaicking plan) can then be used to estimate the difference between the desired pointing attitude of the mosaicking plan and the current attitude so that corrections can be made.

A similar technique can also be used to assist in feature tracking. In this case, the feature points from a previous image are mapped onto the current image space by using the estimated size and perspective change of the object. Once the correspondence has been obtained, a refined estimate of the change in both object size and perspective can be incorporated into the next pointing operation to permit more accurate capture of the desired feature location.

Figure 3 shows a representative result of feature-point detection. Gabor filters and pattern matching between two consecutive frames of Triton images are used.

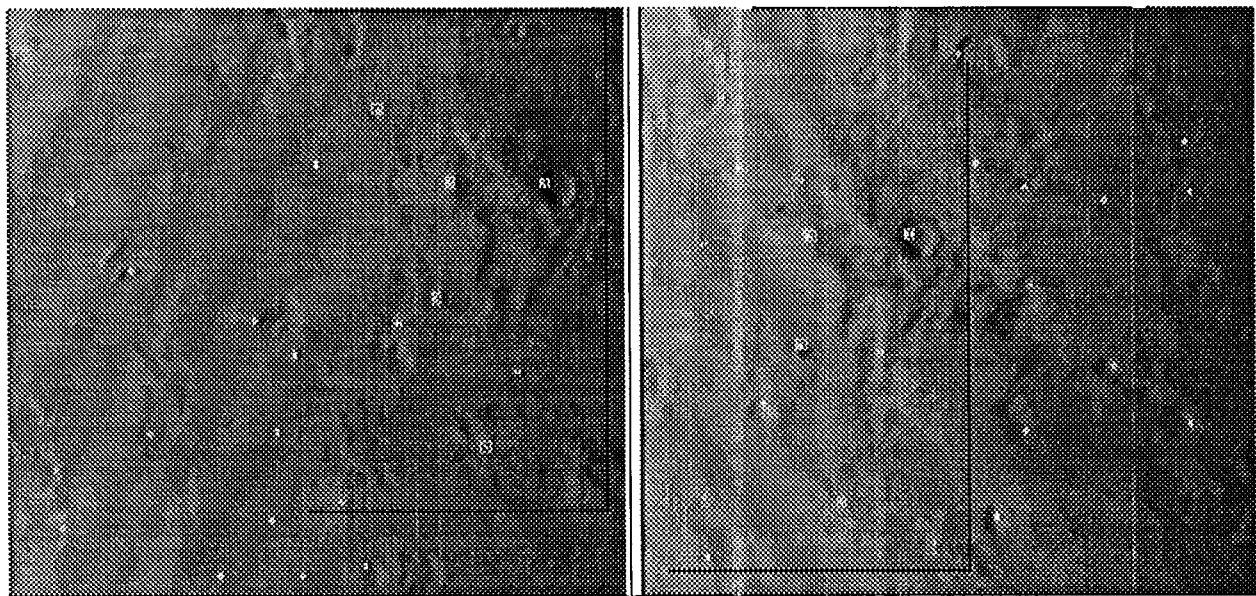


Figure 3 Triton images showing feature-point detection and pattern matching

2.3 AUTONOMOUS PLANNING OF MOSAICKING

To carry out an autonomous mosaicking operation and feature tracking, we need to know the apparent object size in every frame. In the case of a linear flyby of a slow-spinning asteroid, the rectangular bounding technique discussed in Section 2.1 provides a good estimate of the target size whenever the entire target is within the same field-of-view and the length (or perimeter) of the rectangle can be used as the target size. Such an estimate is relatively immune to small local variation of the boundary points detected from the image.

The target's size as it appears in the image plane can be parameterized as the inverse function of a second-order polynomial. By collecting a series of measurements of the object size, a least-squares solution can be found for this function. As the spacecraft approaches the target, such an estimate can be improved continuously by using new estimates of the target size. Although the bounding rectangle can be calculated only when the entire object is within the field of view, frame-to-frame local feature matching can be used to provide the new estimate of the target size. Therefore, the prediction of the target size at any given time prior to the mosaicking operation can be improved continually.

Another important element in the planning of the mosaicking process is the mosaic size. The rectangular bounding approach naturally leads us to design the rectangular mosaicking sequence, and the aspect ratio of the bounding rectangle can be used as the ratio of the horizontal and vertical directions of the mosaic images. To capture high-resolution images, one would like to have a large number of mosaic images. However, if the total number of mosaic images is too large, complete coverage of the entire target may not be possible. Therefore, the "best" mosaic size can be determined by using the continuously improving size prediction; the "best" starting time for mosaicking can also be computed.⁶ A representative mosaic sequence carried out by our approach is shown in Figure 4.

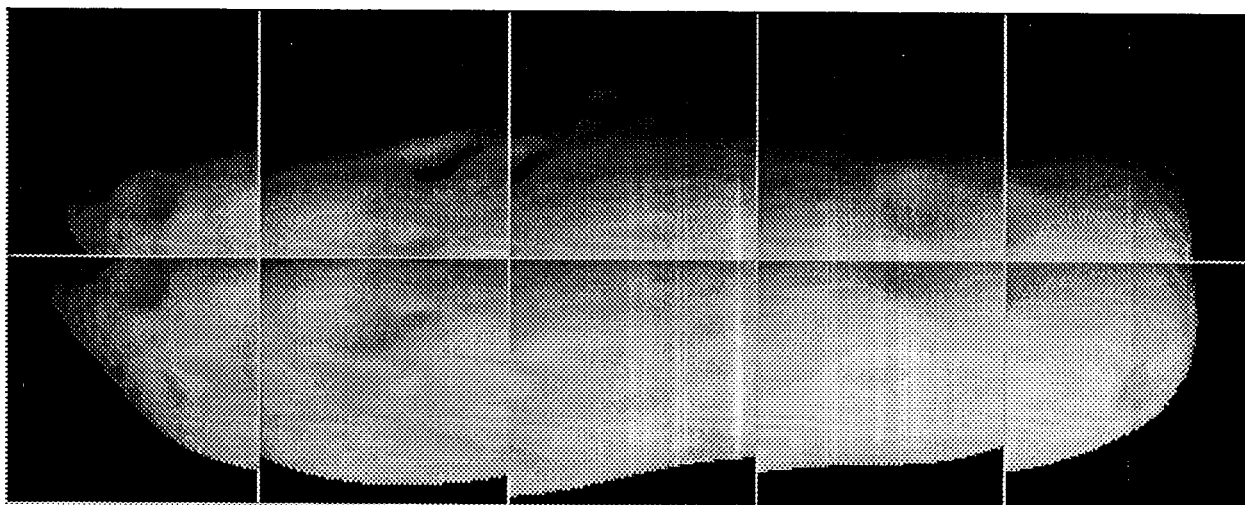


Figure 4 Composite target image resulting from autonomous planning of mosaicking

3 AFAST 3-D VISUALIZATION TESTBED FOR SPACE FLIGHT

The AFAST project at JPL, has developed a 3-D graphics testbed to be used in the development of an image-based, autonomous spacecraft-pointing system for future planetary exploration. This graphics testbed has been implemented in C++ and SGI/GL and runs on Silicon Graphics workstations.

One of our major concerns, when designing the system, was that it be as general and flexible as possible. To achieve this generality, the testbed was designed to be a stand-alone graphics engine that has no built-in knowledge of our specific application. We use SGI's hardware-1 rendering capabilities and provide appropriate "hooks" allowing the user to integrate the application code with the graphics software through common UNIX socket communication.

Because the need to generate highly realistic scenes and to allow the user to view planetary bodies from different viewpoints in real time is paramount in the development of our pointing system, we allow the user to drive the graphics testbed through an external simulation, or by precomputed data files. The user can also configure the system at run time. Spacecraft trajectory information, a planetary body ephemeris, star maps, and texture images are all chosen by the user at run time and are specified in a configuration file that is parsed by the graphics software. In addition, the user can load computer-aided design (CAD) files containing spacecraft or planetary models. Figure 5 shows a functional block diagram for such a graphics testbed.

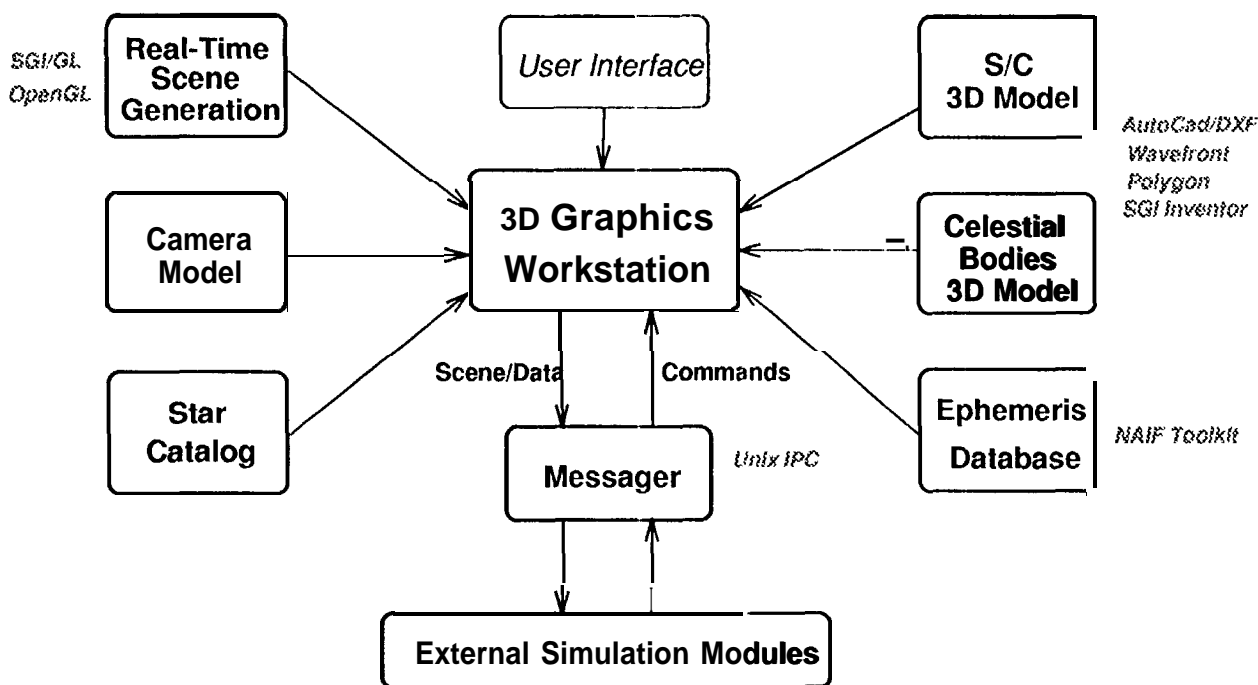


Figure 5 AFAST 3-D visualization testbed for space-flight simulation

The look and feel of the graphics presentation can also be reconfigured at runtime. The user has the option of opening up to seven graphics viewports and placing those viewports at any location on the computer monitor.

Various 3-D views, such as "wingman view", where the viewer flies alongside the spacecraft, "panoramic view", where the viewer can sit at a chosen point in space and look at another chosen point, and "camera boresight", where the viewer can look down the boresight of the spacecraft's imaging camera, are supported. In addition, 2-D views that display the spacecraft's trajectory and various statistical data are also supported.

The flyby scenario discussed in Section 2 has been implemented and tested successfully on this visualization testbed. A video demonstration of the flyby scenario is being presented.

4 CONCLUSIONS AND FUTURE WORK

In this paper, we have shown the extension of our work to the acquisition, tracking, and mosaicking of irregularly shaped bodies.

Our approach to the realization of an intelligent, autonomous, image-based pointing and tracking system has been demonstrated successfully. The 3-D space-flight visualization testbed has also been improved greatly and has enabled a successful demonstration of a planetary asteroid flyby to show our capabilities in autonomous searching, detecting, tracking, and mosaicking for a slow-spinning asteroid.

We are currently developing a robust Kalman filter-based tracking methodology which is applicable to any celestial body, including large planets, asteroids, and comets. Significant effort is also under way to develop robust, efficient, feature-detection algorithms. The technical issues in establishing onboard 3-D topographical model capability for a fast-spinning small body will also be addressed.

5 ACKNOWLEDGMENT

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6 REFERENCES

- [1] C.C. Chu, D. Zhu, S. Udomkesmalee, and M. Pomerantz, "Realization of autonomous image-based spacecraft pointing systems: planetary flyby example," *Proc. SPIE*, Vol. 2221, 1994, pp. 27-40.
- [2] R.S. Hudson and S.J. Ostro, "Shape of asteroid 4769 Castalia (1 989 PB) from the inversion of radar images," *Science*, Vol. 263, Feb. 18, 1994, pp. 940-943.
- [3] C. Padgett and D. Zhu, "Feature based tracking and recognition for remote sensing," *Proc. SPIE*, Vol. 2466, 1995.
- [4] S. Udomkesmalee, G.F. Sevaston, and R.H. Stanton, "Toward an autonomous feature-based pointing system for planetary missions," *Proc. SPIE*, vol. 1949, 1993.
- [5] S. Udomkesmalee, D. Zhu, and C.C. Chu, "Image processing for planetary limb/terminator extraction," submitted to *CVGIP*, 1994.
- [6] D. Zhu and C.C. Chu, "Characterization of irregularly shaped body," *Proc. SPIE*, Vol. 2466, 1995.